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ABSTRACT

Ultrasonic waves form a useful nondestructive evaluation (NDE) probe for determining physical, microstructural, and mechanical properties of materials and parts. Noncontacting laser ultrasonic methods are desired for remote measurements and on-line manufacture process monitoring. Researchers at the Idaho National Engineering & Environmental Laboratory (*INEEL*) have developed a versatile new method for detection of ultrasonic motion at surfaces. This method directly images, *without the need for scanning*, the surface distribution of subnanometer ultrasonic motion. By eliminating the need for scanning over large areas or complex parts, the inspection process can be greatly speeded up. Examples include measurements on parts with complex geometries through resonant ultrasound spectroscopy and of the properties of sheet materials determined through anisotropic elastic Lamb wave propagation. The operation and capabilities of the *INEEL Laser Ultrasonic Camera* are described along with measurement results.

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INTRODUCTION

This paper describes a powerful new method to optically image ultrasonic motion at the surface of materials. A device has been constructed that produces images at standard video frame rates (~30Hz) of the out-of-plane ultrasonic motion over a large surface. Adaptive interferometry is employed utilizing the photorefractive effect in optically nonlinear materials [Stepanov, 1991, and Yeh, 1993]. The device is termed the *INEEL Laser Ultrasonic Camera* and is shown in figure 1.

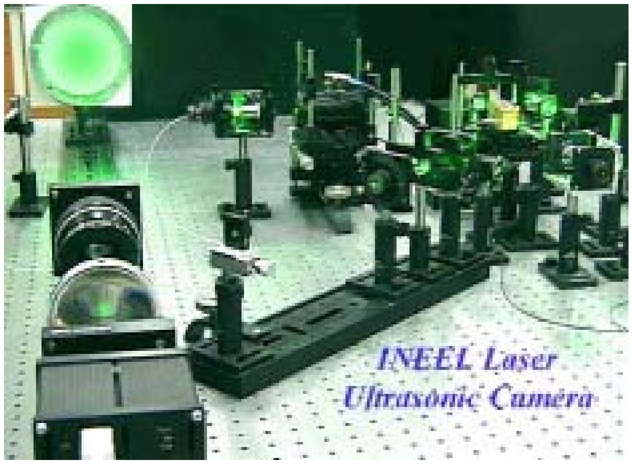


Figure 1. The camera apparatus.

As with other laser ultrasonic detection methods, optical interference is employed to demodulate the very small phase shift that a laser beam experiences upon scattering from a surface undergoing ultrasonic motion. A hologram of the phase information is produced within a photorefractive material and an output beam scattered from this hologram is produced whose intensity is directly proportional to the surface vibration amplitude, for small ultrasonic displacements. Utilizing this approach, no post-processing is required to produce images of the surface vibrational motion over large areas. The fundamental approach and application to imaging of resonant and traveling wave modes in metal plates are described.

Many optical techniques for measuring ultrasonic motion at surfaces have been previously developed for use in applications such as vibration measurement and laser ultrasonics. Most of these methods have similar sensitivities and are based on time domain processing using homodyne, heterodyne, Fabry-Perot [Wagner, 1990], and, more recently, photorefractive interferometry [Ing, 1991]. Generally, the methods described do not allow measurement at more than one surface point simultaneously, requiring multiple beam movements and scanning in order to produce images of surface ultrasonic motion over a large area. Electronic speckle interferometry, including shearography, does provide images directly of vibrations over large surface areas. This method has proven very durable in the field for large displacement amplitudes of several wavelengths. Full-field imaging of traveling ultrasonic waves using digital shearography has been recently reported with sensitivity in the nanometer range [Bard, 1998]. With this method, optical interference occurs at the photodetector surface of the camera that records the speckle image from the surface. Multiple image frames are typically recorded and processed in a computer to produce an output proportional to surface displacement. In contrast, the technique described in this paper records the demodulated ultrasonic motion in a single image frame, produces an output image directly not requiring further processing, and the intensity of the image is inherently proportional to small ultrasonic displacements.

An important nondestructive evaluation measurement technique is to record the vibration mode spectrum of a material part or structure, excited by a random or a driven source (e.g. acoustic coupling or shaker table). The vibration mode spectrum fully describes the part dimensions and material properties, including defects. Application of this technique has spawned a new NDE method known as Resonant Ultrasound Spectroscopy (RUS) that has been found useful for characterizing components and structures of many diverse shapes and sizes [Migliori, 1999]. The *INEEL Laser Ultrasonic Camera* is well suited for the resonant ultrasound method of inspection for determining physical and mechanical properties of manufactured parts or for in-process monitoring and control. Ultrasonic motion of all types in most materials can be measured and also imaged with this new approach. Examples are desribed illustrating noncontacting and imaging capability.

Anisotropic elastic properties of sheet materials often result from microstructural texture and residual or applied stress. These effects in plates can be determined by measuring the propagation of Lamb waves in different directions. Electromagnetic acoustic transduction and laser ultrasonic methods provide noncontacting approaches for generating ultrasonic waves in plates that are often desired for application to industrial and processing environments. Examples of employing the INEEL approach are presented that produce a real-time measurement of the antisymmetric Lamb wave mode in all planar directions simultaneously. Continuous excitation is employed enabling the data to be recorded and displayed by a CCD camera. Analysis of the image produces a direct quantitative determination of the phase velocity in all directions showing plate anisotropy in the plane.

DYNAMIC HOLOGRAPHIC INTERFEROMETRY

Very small ultrasonic displacements can be detected by optical interferometry. A small optical phase shift is produced on a laser beam scattered from a material surface undergoing vibration that is given by $\Delta\varphi = \frac{4\pi\xi}{\lambda}$, where ξ is the ultrasonic displacement amplitude and λ is the optical wavelength. Since, optical wavelengths are very small, here $\lambda = 532\ nm$, small phase shifts corresponding to displacements in the subnanometer range can be readily detected. Nonlinear optics offers a new approach to performing interferometry that can perform several functions over an entire image simultaneously; thereby, providing an imaging approach to this very sensitive displacement measurement method. In particular, photorefractivity employs optical excitation and transport of charge

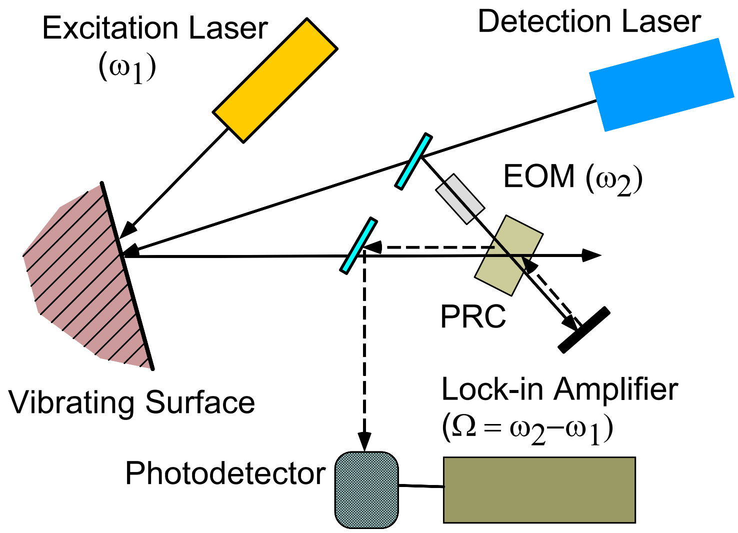


Figure 1. Basic wave mixing geometry for dynamic photorefractive holographic measurement of ultrasonic waves at the surface of a plate. PRC is the photorefractive crystal and EOM is an electro-optic phase modulator.

carriers that are produced from the interference pattern developed inside specific materials. A spatial and temporal charge distribution results in a hologram of the phase information impressed onto the optical signal beam by the vibrating surface. Several optical frequency domain measurement methods of vibration have been proposed using photorefractive two and four-wave mixing in select materials [Huignard, 1981 and Hofmeister, 1992]. These typically provide a time averaged response that is a nonlinear function of the specimen vibration displacement amplitude. The method reported here measures the photorefractive grating produced at a fixed beat frequency between the phase modulated signal and reference beams. This technique allows use in a manner that directly measures vibration amplitude and phase with a response proportional to the Bessel function of order one, providing a direct output linear for small amplitudes. The method accommodates rough surfaces, exhibits a flat frequency response above the photorefractive response cutoff frequency and can be used for detecting both standing and traveling waves [Hale, 1996; Telschow, 1998, 1999].

A diode pumped solid state laser source at 532 nm, 5 W, was split into two legs for signal and reference beams, as shown in figure 1. The signal beam was reflected off a specimen plate driven continuously by a piezoelectric or laser transducer. Flexural waves were excited in the plate either as resonant standing waves or as traveling Lamb waves. The wave displacement at the plate surface modulated the phase of the signal beam at the frequency ω_1. The reference beam was phase modulated at the frequency ω_2 by an electro-optic modulator at a fixed modulation depth. The modulated beams were then combined and interfered inside a bismuth silicon oxide (BSO) photorefractive crystal as shown. The details of this arrangement and its operation have been previously described [Hale, 1997].

The optical interference grating and subsequent charge migration within the crystal generate a corresponding space charge electric field distribution. The dynamic behavior of this field is controlled by the charge carrier mobility and trapping that produces, in the diffusive operation regime, a single relaxation time (τ) response controlled by the concentration of available charge trapping sites and the light intensity. In the above configuration, the photorefractive crystal acts as a mixing and low-pass filtering element, providing the benefits of lock-in detection. Therefore, the space charge field responds to slowly varying phase modulations occurring within the material response time, allowing only the terms around the difference frequency $\Omega = \omega_s - \omega_r$, $\Omega\tau \le 1$ to be important. The space-charge field modulates the local refractive index through the linear electro-optic effect. This effect creates a diffraction grating within the crystal that contains the low frequency phase information desired.

In the four-wave mixing detection approach, the reference beam transmitted through the crystal is reflected back on itself to diffract off the grating. The output of this beam is then selected by another beamsplitter in the signal path, not shown. A narrow beam diameter of about 2 mm was used for making point measurements, while the beam was expanded to cover roughly a 50 mm diameter on the plate for imaging. Subsequently, a photodetector, coupled with conventional electrical lock-in methods, recorded the point displacement amplitude and phase or an image was captured with a CCD camera at 30 Hz frame rates.

MEASUREMENTS OF VIBRATIONAL RESONANT MODES

A diagram of a 38 mm (1.5 inch) square, 0.38 mm (0.015 inch) thick, stainless steel 304 plate specimen is shown in figure 2; the plate can be driven piezoelectrically at one corner or by laser thermoelastic heating at any position, points referred to later are designated as A, B, C. An all optical method for vibration measurement can be implemented if an optical excitation source is used in conjunction with the optical detection scheme. Absorption of laser light within a solid occurs within a small distance from the surface determined by the optical absorption in the material. The resultant

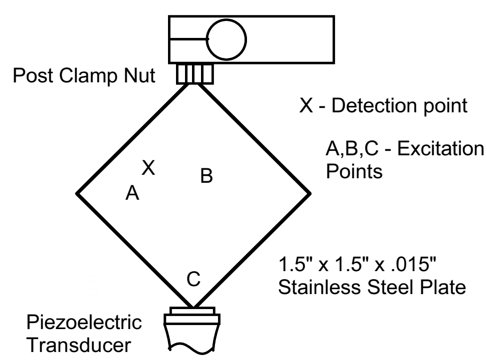


Figure 2. Stainless steel plate geometry.

heating of the sample surface produces a strain that is modulated in the same manner as the excitation source is modulated, i.e. chopped. Optical excitation offers significant potential for selectively exciting certain vibrational modes as the region of excitation can be controlled to enhance the response of one vibrational mode over another. Therefore, optical excitation offers selectivity in addition to being noncontacting.

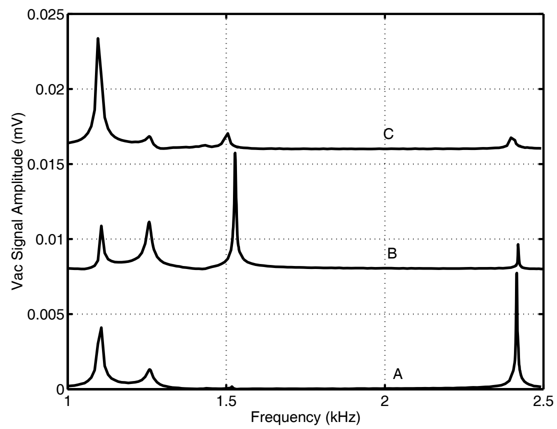
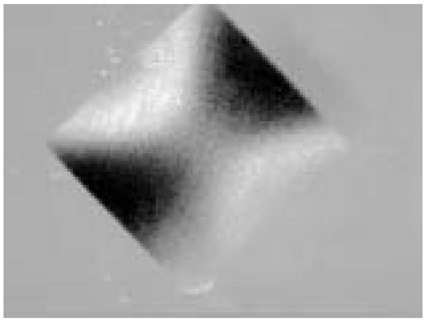


Figure 3. Vibrational response at point X with the source laser focused at positions A, B, and C.

A continuous wave 700 mW average power diode laser beam was directed onto the sample surface to excite the resonant vibrational motion. An acousto-optic modulator chopped the excitation source producing a modulation component at the frequency of interest. The chopping was synchronized with the electro-optic modulator as the measurement frequency was swept through several vibrational modes. Figure 3 shows the effect of moving the laser excitation region around the plate comparing the response of two modes with very different nodal line patterns. Two of the plate modes identified in figure 3 include one with nodal lines traversing across the plate from corner to corner, at 1.5 kHz, and one with a vertical nodal line from the top corner to the bottom and two parallel lines closer to the left and right corners, at 2.4 kHz. The first of these is better described in the images of figure 4 below. The excitation points, A,B,C illustrated in figure 3 were used to show how the optical source position selects between these two modes. Excitation at point A, selected against the 1.5 kHz mode, B selected against the 2.4 kHz mode and C selected against both modes. Greater excitation occurs when the optical absorption spatial profile matches the vibrational mode spatial profile.

Vibration Imaging

Since optical interference and the charge transfer effects occur throughout the photorefractive material, the single point detection method described above can be generalized to that of an image of the vibration over the surface of the plate. The volume character of the photorefractive process creates a grating distribution that locally records the phase modulation measured from each point of the specimen surface as long as the surface is accurately represented within the interference volume. The output beam intensity from the detection process can be recorded with a CCD camera. Each pixel records the local phase information from a point on the specimen producing an output proportional to that point's displacement. This capability for imaging is a significant enhancement of the photorefractive spectral measurement technique compared with other



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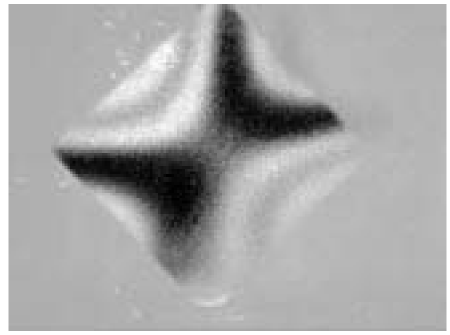

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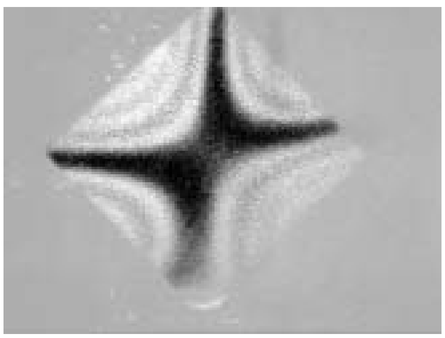

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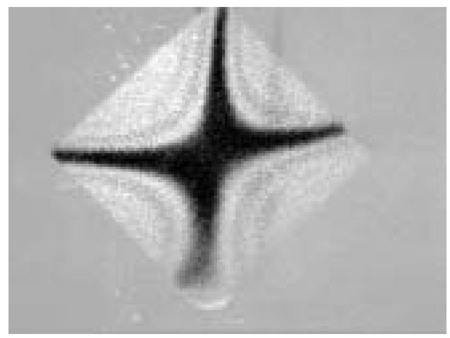

d

Figure 4. Vibrational images of a free square plate driven at 1.5 kHz by a piezoelectric transducer at the lower corner, maximum amplitude is approximately (a) 45 nm, (b) 90 nm, (c) 180 nm, (d) 270 nm.

optical interferometric methods as it provides real-time full-field measurement at virtually any vibration frequency.

A two-wave approach, based on polarization rotation through anisotropic self-diffraction, was used for imaging as it offered improved light throughput from diffusely reflecting surfaces compared to the four-wave method. Figure 4 shows images of the mode at 1.5 kHz, excited by a contact piezoelectric transducer at one corner. A piezoelectric excitation source was used in order to generate displacements larger than the approximately 80 nm produced by the available optical source. The nodal lines are clearly defined, and the relative phases of the vibration displacements are indicated by the light and dark areas. The entire modal pattern can be made to switch from light to dark by varying the offset frequency, $\Omega/2\pi$, between the object and reference excitations. This provides a powerful tool for visual mode searching and suggests processing methods that can be employed to enhance the detectability of specific modes.

The minimum detectable displacement in the imaging mode (~0.1 nm) is much larger than for the point detection method (~2 pm) as no post electronic lock-in processing was performed. Figure 4 illustrates the fact that the intensity is proporional to a Bessel function of order one, which produces a limited response as the vibration amplitude is increased. The vibration response signal becomes nonlinear for amplitudes greater than about 20 nm and peaks at 45 nm for laser wavelength of 532 nm. This fact makes the photorefractive approach primarily useful for small vibration amplitudes where linear response is obtained. For vibrating surfaces with large overall vibration amplitudes, the position on the surface where the peak response is observed moves closer to nodal positions. The result then produces an image resembling the shape of the nodal points within the vibrating surface; hence, the technique becomes a "nodal line" indicator for large vibration amplitudes.

MEASUREMENTS OF TRAVELING WAVES

Single point measurements of nonresonant traveling waves were performed by scanning a narrow signal beam across a plate surface along a radius from the excitation point of a driven metallic plate. The lock-in demodulated signal provided both the amplitude and phase at each measurement point. Even though the wave was not stationary, the amplitude and phase results were recorded to show the wave motion as a time frozen picture of the spatial waveform, see figure 5. The lowest flexural (antisymmetric Lamb) wave mode, was excited at the origin of an isotropic nickel plate of thickness 0.13mm, by a piezoelectric transducer driven continuously. The measured displacement normal to the surface of the wave traveling radially outward from the excitation point agreed well with that predicted displacement from classical flexural wave plate theory [Morse, 1968], as indicated in figure 5.

The flexural mode phase velocity is well known from the elastic theory for plate waves and allows the wavelength to be predicted based on given material elastic constants. The wavelength was determined from the signal phase exhibiting the wave dispersion for this mode. Figure 6 shows the good agreement achieved between the measured and predicted wavelengths over a large frequency range using the known elastic constants for nickel.

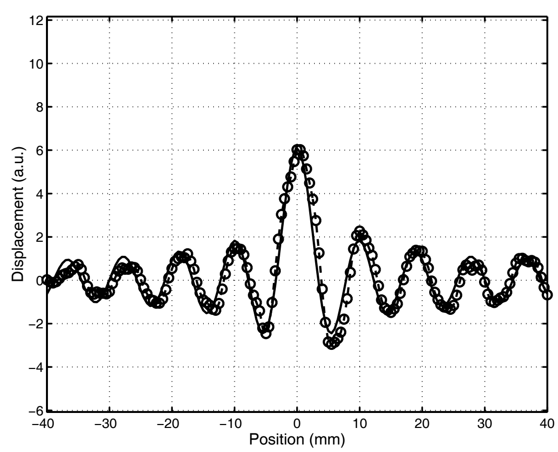

Figure 5. Measured and calculated waveforms of traveling flexural waves emanating from a central point on a nickel plate.

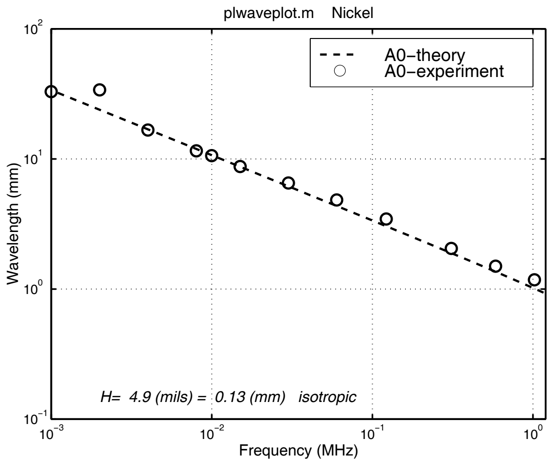

Figure 6. Wavelength of the antisymmetric traveling Lamb wave mode as a function of frequency compared to that predicted for the 0.13 mm thick nickel plate.

TRAVELING WAVE IMAGING MEASUREMENTS

Figure 7 shows images of the traveling wave modes of the nickel plate obtained with the two-wave mixing method. The flexural mode wavefronts traveling outward from the center are clearly defined, and the relative phase of the displacements is readily distinguishable. The figure shows image data frames at two different frequencies that have the background subtracted. For qualitative inspection of two dimensional waveforms from the CCD output, the eye integrates over multiple video frames. This makes it possible to easily detect subtle patterns that might not be as easily extracted by digital image processing methods. Also the entire pattern can be made to change its phase continuously at the frequency, Ω, perhaps about 2 Hz, so that the appearance is that of waves emanating from the center and traveling outward. This is physically equivalent to the actual traveling wave motion except that viewing of the wave has been slowed to a much smaller observation frequency that is held constant and independent of the actual wave frequency. The photorefractive process yields a true picture of the actual wave vertical displacement motion and does not require any additional processing to generate the images of figure 7.

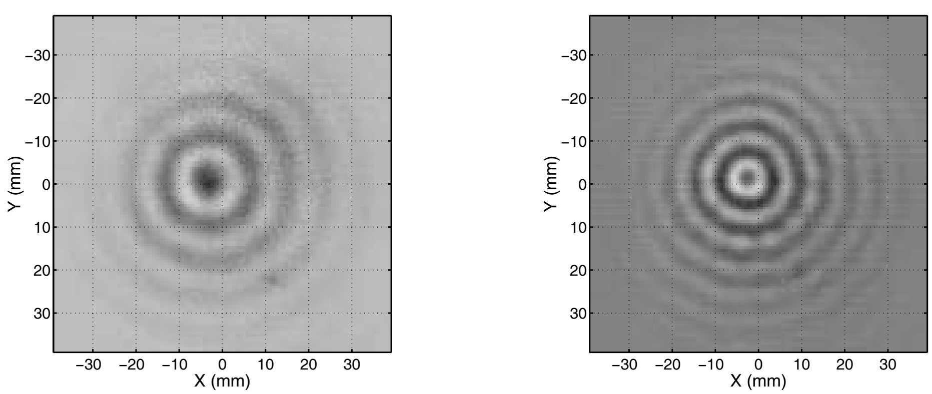

Figure 7. Images of traveling Lamb waves in nickel at 15 kHz (left) and 30 kHz (right).

If the specimen is elastically anisotropic, then the wave speed varies with the propagation direction. Figure 8 shows this type of behavior for traveling waves in a sheet of carbon fiber composite. The carbon fiber sheet was approximately 0.18 mm thick with the fibers aligned parallel to the vertical direction. The matrix is an isotropic resin material. The highly oblong wavefront pattern seen in figure 8 shows the anisotropy clearly and immediately. Clearly, a great deal of information about the anisotropic elastic properties of the sheet can be obtained directly from this imaging measurement technique.

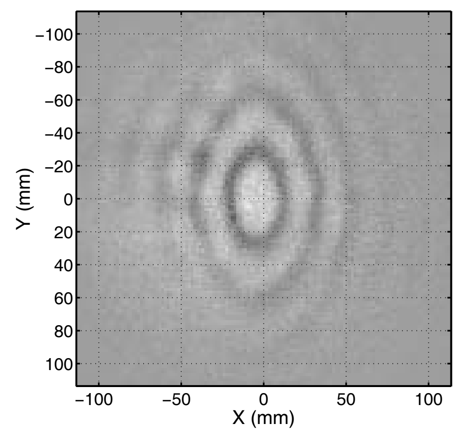

Figure 8. Traveling wave in a an anisotropic composite sheet at 37.8 kHz.

CONCLUSIONS

A photorefractive optical lock-in resonant and traveling wave measurement method has been described. Nonlinear optical wave-mixing was employed for recording and reading a dynamic phase hologram of the ultrasonic displacement at both individual points and as an image over the surface. The signal intensity is directly proportional to the amplitude of the vibration being measured and both ultrasonic displacement and phase are recorded. Point measurements produce a spatial snapshot of the amplitude and phase of the resonant vibrational or traveling wave motion. Direct two-dimensional surface images were obtained by expanding the collection optics and imaging the output beam from the photorefractive material. These images show the resonant behavior of the part as well as the ultrasonic wavelength and wavefront shape of traveling waves providing a quantitative method for NDE of flaws and obtaining dimensions, elastic properties and anisotropy of materials. The method is capable of flat frequency response over a wide range above the cutoff of the photorefractive effect and is applicable to rough surfaces.

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